ADAPTIVE ROUTING AND WAVELENGTH ASSIGNMENT IN ALL-OPTICAL NETWORKS

C. BALAKRISHNAN

Roll No: 211EC4101

Under the guidance of

Prof. S. K. Das

Department of Electronics & Communication Engineering

National Institute of Technology

Rourkela

2013

ADAPTIVE ROUTING AND WAVELENGTH ASSIGNMENT IN ALL-OPTICAL NETWORKS

A THESIS SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Communication & Signal Processing

By

C. BALAKRISHNAN

Roll No: 211EC4101

Under the guidance of

Prof. S. K. Das

Department of Electronics & Communication Engineering

National Institute of Technology

Rourkela

2013

National Institute Of Technology
Rourkela

CERTIFICATE

This is to certify that the thesis entitled," **ADAPTIVE ROUTING AND WAVELENGTH ASSIGNMENT IN ALL-OPTICAL NETWORKS**" submitted by C. BALAKRISHNAN in partial fulfillment of the requirements for the award of Master of Technology degree in **Electronics and Communication Engineering** with specialization in "**Communication & Signal Processing**" during session 2012-2013 at National Institute of Technology, Rourkela (Deemed University) and is an authentic work by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any Degree or Diploma.

Date:

Prof. S. K. Das
Dept. of ECE
National Institute of Technology
Rourkela-769008
Email: dassk@nitrkl.ac.in

৳# Acknowledgment

This work would have not been possible without the guidance and the help of several individuals who in one way or another, contributed and extended their valuable assistance in the course of this study.

My utmost gratitude to **Prof. S. K. Das**, my dissertation adviser whose sincerity and encouragement I will never forget. **Prof. Das** has been my inspiration as I hurdle all the obstacles in the completion of this research work and has supported me throughout my project work with patience and knowledge whilst allowing me the room to work in my own paradigms.

Sincere thanks to **Prof. S .K. Patra, Prof. K. K. Mohapatra, Prof. S. Meher, Prof. S. Ari, Prof. S. K. Behera, Prof. P. Singh** and **Prof A. K. Sahoo** for their constant cooperation and encouragement throughout the course. I also extend my thanks to entire faculties and staffs of Dept. of Electronics & Communication Engineering, National Institute of Technology, Rourkela who have encouraged me throughout the course of my Master's Degree.

.

C. Balakrishnan

balakrishnannit@gmail.com

Abstract

In WDM all-optical networks without wavelength conversion capabilities, signals must travel on the same wavelength over long distances. During transmission the signal quality gets degraded due to linear and non-linear physical layer impairments resulting in high BER. Many PLI aware RWA algorithms have been proposed in the literature, which consider the effect of the impairments on the signal quality. We consider the effect of component crosstalk and ASE noise. The adaptive RWA algorithm presented incorporates QoS information at both the routing and wavelength assignment steps to mitigate the effect of crosstalk. Different routing strategies are used in the algorithm to compare the computational complexity and the blocking performance of the network.

List of Abbreviations

QoS	Quality of Service
Q-Factor	Quality Factor
ASE	Amplifier Spontaneous Emission
PLI	Physical Layer Impairments
WDM	Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
SP	Shortest Path
LQ	Least Q-Factor
OEO	Optical-Electronic-Optical
HEC	Hetero-wavelength Crosstalk
HOC	Homo-wavelength Crosstalk
EDFA	Erbium Doped Fiber Amplifier
BER	Bit Error Rate
OXC	Optical Cross-Connect
RWA	Routing and Wavelength Assignment
ITU	International Telecommunication Union
SONET	Synchronous Optical Network
IP	Internet Protocol
SLA	Service Level Agreement
OSNR	Optical Signal to Noise ratio
UNI	User Network Interface
NNI	Network to Network Interface
SMF	Single Mode Fiber
DCF	Dispersion Compensated Fiber
MPLS	Multi-Protocol Label Switching
NF	Noise Figure

List of Symbols

λ	Wavelength
μ	Average
σ	Standard deviation
σ^2	Variance

List of Figures

Fig.1	Optical layer connections managed using a centralized NMS	7
Fig.2	Overlay model based on distributed control plane	8
Fig.3	Peer model where the same control plane software is run on all the layers	8
Fig.4	A simple WDM transmission system	9
Fig.5	Different PLI aware RWA schemes	14
Fig.6	Crosstalk due to the non-ideal filtering	16
Fig.7	Crosstalk generation in OXC	17
Fig.8	Example of an optical network that may induce component crosstalk	20
Fig.9	Topology considered for simulation	25
Fig.10	Blocking probability for SP method when the number of wavelengths = 10	27
Fig.11	Blocking probability for SP method when the number of wavelengths = 12	27
Fig.12	Blocking probability for alternate route method when the number of Wavelengths = 10	29
Fig.13	Blocking probability for alternate route method when the number of Wavelengths = 12	30
Fig.14	Blocking probability for k-SP (k=7) method when the number of Wavelengths = 10	31
Fig.15	Blocking probability for k-SP (k=7) when the number of wavelengths = 12	31
Fig.16	Blocking probability for disjoint route method when the number of Wavelengths = 10	32
Fig.17	Blocking probability for disjoint route method when the number of Wavelengths = 12	33

List of Tables

1. Physical parameters for the simulated network 26
2. Optimum Q-Factor policy for SP route computation 28
3. Least Q-Factor policy for SP route computation 28
4. Optimum Q-Factor policy for disjoint route computation 33
5. Least Q-Factor policy for disjoint route computation 34

CONTENTS

Certificate i

Acknowledgement ii

Abstract iii

List of Abbreviation iv

List of Symbols v

List of Figures vi

List of Tables vii

1. INTRODUCTION **2**

1.1 Introduction 2

1.2 Proposed Work 3

1.4 Organization of the Thesis 3

2. ALL-OPTICAL NETWORKS **6**

2.1 Evolution 6

2.1.1 Control Plane models 7

2.2 WDM/DWDM Technology 9

2.3 PLI aware Routing and Wavelength Assignment 10

2.3.1 Routing strategies 10

2.3.2 Wavelength Assignment methods 12

2.3.3 QoS-aware RWA 13

2.3.4 Linear Impairments 14

2.3.5 Non-Linear Impairments 15

2.4 Crosstalk and ASE noise in all-optical networks 15

2.4.1 Amplifier Spontaneous Emission (ASE) noise 15

2.4.2 Crosstalk in multi-wavelength switched networks 16

3. ADAPTIVE ROUTING AND WAVELENGTH ASSIGNMENT **20**
3.1 Network Model 20
3.2 Q-Factor 21
3.3 Proposed Mechanism 21
3.4 Algorithm 22

4. SIMULATION AND RESULTS **25**
4.1 Simulated Topology 25
4.2 Simulation Result for Shortest Path method 26
4.3 Simulation Result for Alternate Route method 29
4.4 Simulation Result for k-SP method 30
4.5 Simulation Result for disjoint route method 32

5. CONCLUSION AND FUTURE WORK **36**
5.1 Conclusion 36
5.2 Future Work 36

BIBLIOGRAPHY 37

CHAPTER 1

INTRODUCTION

Introduction

Proposed Work

Organization of the Thesis

1.1 Introduction

Optical networks have evolved from opaque (O-E-O conversion at all nodes) and translucent (few nodes version capabilities) architectures to all-optical or transparent (no O-E-O conversion) architecture. All-optical networks are a new generation of optical networks in which the nodes (the wavelength router's) route signals in the optical domain. Since signals are not regenerated at the nodes, optical leaks called crosstalk propagate and accumulate over the lightpath which interferes with the desired signal causing degradation of the signal quality.

Due to non-ideal filtering characteristics of the nodes, there are two forms of linear crosstalk that occur in the network i) HEC(hetero-wavelength) or out-of-band crosstalk which arises from channels on same input route but operating at different wavelengths. ii)HOC(homo-wavelength) or in-band crosstalk due to crosstalk signals occupying the same nominal wavelength as the desired signal. Out-band crosstalk does not cause signal quality deterioration since it can be removed by filtering while in-band crosstalk is difficult to eliminate completely. Nevertheless, with carefully designed QoS aware RWA algorithms it is possible to reduce the effect of crosstalk.

When the physical layer is considered ideal, the SLA's usually employed are based on bandwidth, and end-to-end delay etc. When the RWA algorithms are PLI-aware they need to accommodate the SLA's specific to the optical layer. The SLA parameters normally used are [1]

a) Optical power: The optical power of a signal that reaches the receiver should fall within the dynamic range of the receiver to operate reliably below a specific BER.

b) Bit-Error Rate (BER): It is an important measure of the network performance. As the optical networks evolve achieving higher data rates of 2.5 Gb/s and further, direct measurement of BER takes a considerable amount of time.

c) Q-Factor: Quality-Factor based approach is considered faster compared to the traditional BER test. Q-Factor measures the quality of an analog transmission signal in terms of its signal-to-noise ratio. It takes into account the effect of physical layer impairments which degrades the signal causing bit errors.

Higher the value of Q-Factor, better the OSNR and hence lower the BER. The disadvantage is that when fiber non-linearity is taken into effect the accuracy of the results is questioned.

The Q-Factor is directly related to the BER by $BER = 0.5erfc\left(\frac{Q-Factor}{\sqrt{2}}\right)$using a Gaussian approximation. We use the Q-Factor based approach to study the effect of physical layer impairments on the network performance.

1.2 Proposed Work

PLI-aware RWA algorithms have been proposed in the literature in [2, 3, 4] and in [5].We try to capture the most significant impairments in-band crosstalk and ASE noise, when we estimate the Q-Factor. With carefully designed QoS aware RWA algorithms it is possible to reduce the effect of crosstalk.

Because both crosstalk and wavelength availability depend on the network state, it is important that such RWA algorithms consider only those routes that can meet the wavelength continuity constraint and that dynamically accounts for QoS at route establishment time. Such RWA algorithms are said to be adaptive, and we propose three adaptive RWA algorithms (shortest path, Optimum Q-Factor and Least Q-Factor) that account for the network state both in terms of the existing connections and current QoS at both the routing and wavelength assignment steps to evaluate the network blocking performance.

In our work while evaluating the blocking performance of the proposed adaptive RWA algorithms, different route selection methods have been employed. The blocking performance and computational complexity of the methods like SP, alternate route, k-SP and disjoint route (all possible paths) are evaluated and compared.

1.3 Organization of the thesis

Chapter 2 deals with the evolution of all-optical networks and the associated WDM/DWDM technology, in which optical components are discussed.RWA problem is considered; specific physical layer impairments like Crosstalk and ASE are studied.

Chapter 3 discuss' adaptive routing and wavelength assignment; a network model is presented to describe the process of crosstalk generation and Q-Factor model is described which is used to evaluate the network performance. Lastly adaptive RWA algorithm is explained.

Chapter 4 deals with simulation of a 9-node network topology and the results for various methods that are employed during the RWA process like SP, alternate route, k-SP and disjoint route (all possible paths)

Chapter 5 concludes our work with a brief analysis of the results obtained.

CHAPTER 2

ALL-OPTICAL NETWORKS

Evolution

WDM/DWDM Technology

PLI aware Routing and Wavelength Assignment

Crosstalk and ASE noise in all-optical networks

ALL-OPTICAL NETWORKS

2.1 Evolution

Signal transmission over optical fiber provides advantages like low loss, high bandwidth, low levels of undesirable transmission impairments, immunity to electromagnetic interference and long life-spans. The three low loss windows used for optical communication are in the 0.8, 1.3 and 1.55 μm infrared wavelength bands [6]. The 1.55 μm band has the lowest loss of 0.25dB/km with 1.3 μm band having a loss of 0.5dB/km. Early fibers were multimode fibers with core diameters of 50 to 85mm.The diameter is large compared to the operating wavelength and hence supported multiple propagation modes. Multi mode fiber transmission suffers from intermodal dispersion.

With the advent of single mode fiber transmission, the intermodal dispersion was completely eliminated. The core diameter is about 8 to 10μm, which is a small multiple of the operating wavelength. There was a dramatic increase in the bit rate and distance between regenerators.

Later Erbium Doped Fiber Amplifiers (EDFA) enabled simultaneous amplification at many wavelengths. This allowed the use of multiple wavelengths with each operating at a specific bit-rate. Wavelength division multiplexing (WDM) systems increased the system capacity to a great extent.

Optical layer will move from providing simple transmission pipes to a managed optical network. Higher layer equipments like SONET or IP boxes handle switching and routing of data in the electrical domain after optical-electrical conversion when the optical layer is used only as a transmission medium.

In case of managed optical network, the optical layer handles the functions like switching and routing without the need for an Optical-Electrical-Optical conversion resulting in an all-optical network. All-optical networks are transparent networks referring to the ability of the network to carry data regardless of the protocol or framing structure used.

2.1.1 Control plane models

The optical layer provides circuit switched, high bandwidth connections to its client layer which is usually the SONET box or IP router. Different models have been proposed to manage the optical layer and the client layer. Fig. 1 shows a model in which the optical layer connections are managed using a centralized network management system. In this case there is no direct interaction between the two layers [6].

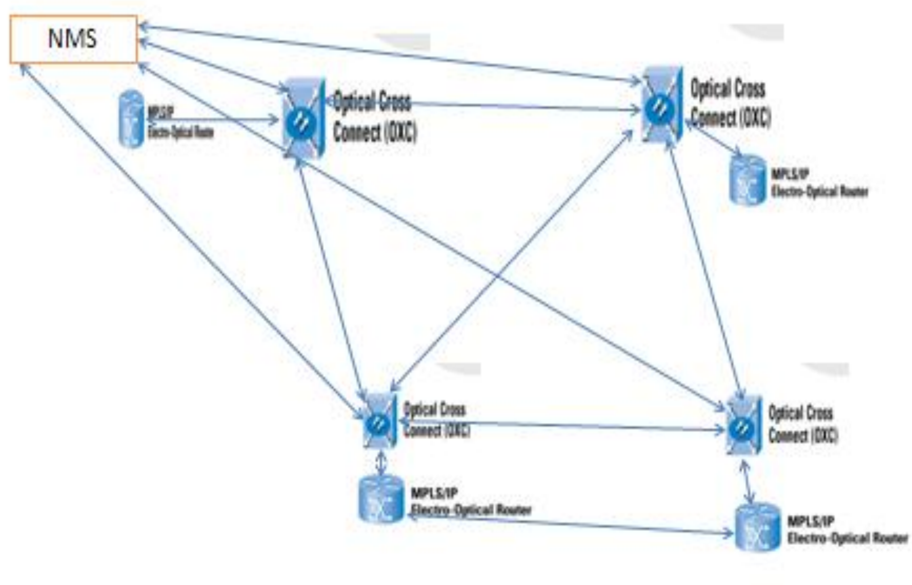


Fig.1 Optical layer connections managed using a centralized NMS

Fig.2 shows an overlay model based on distributed control plane in which there is direct interaction between the client layer and the optical layer. In this model, the optical layer and the client layer have their own control plane. The interaction between the layers happen through a user network interface (UNI) and within the optical layer different sub-networks interact through a standardized network-to-network interface(NNI).This model allows scalability in both the layers independently. In this model the details of the optical layer is hidden from the client layer through the UNI.

2.1 Evolution

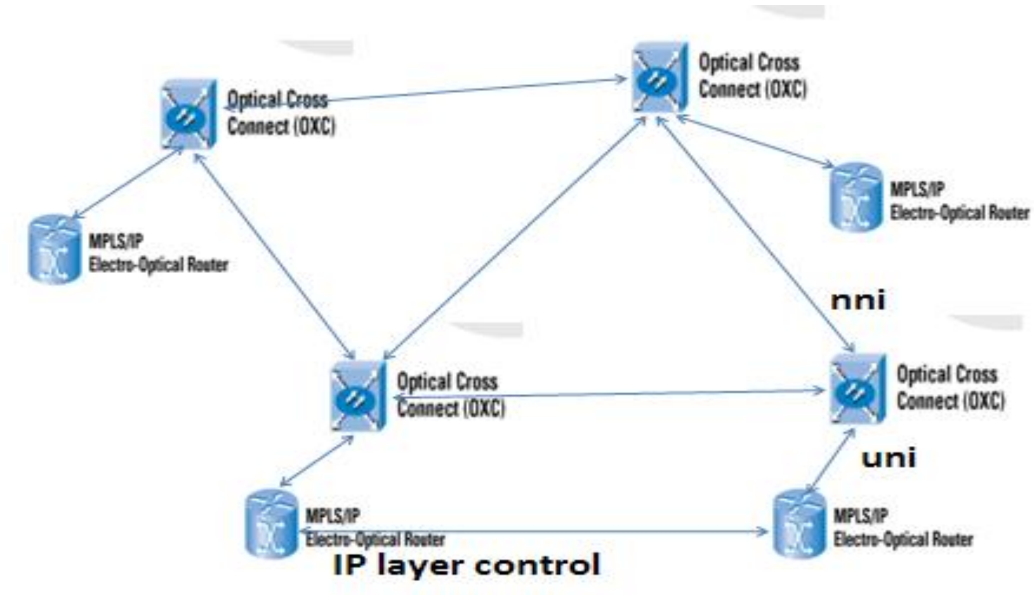


Fig. 2 Overlay model based on distributed control plane

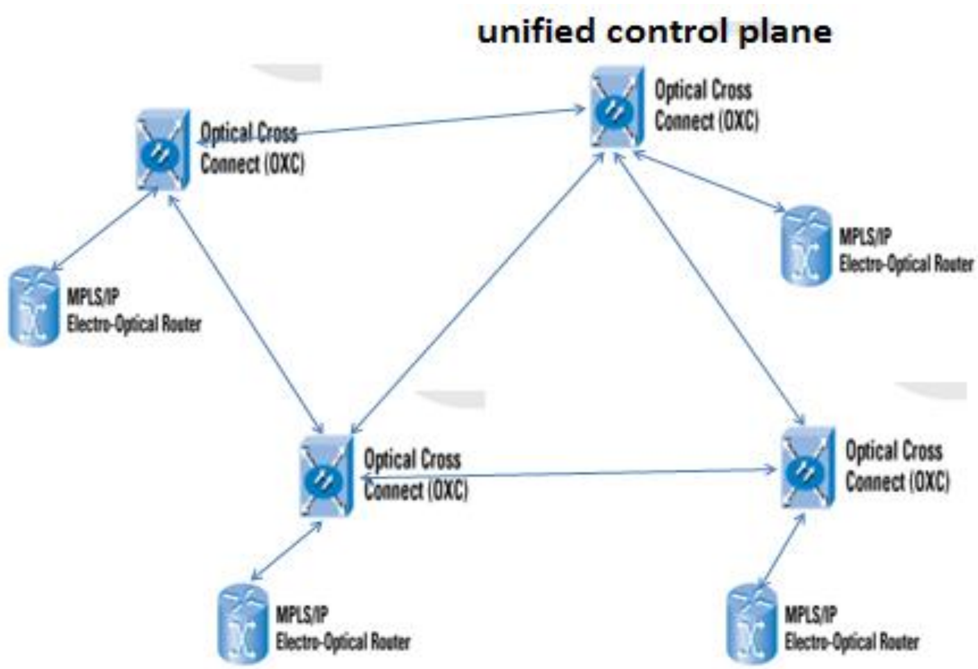


Fig.3 Peer model where the same control plane software is run on all the layers

Fig.3 shows the peer model where the same control plane software is run on the optical layer and the client layer. The Optical Cross Connects (OXC) and IP routers act as peers with the IP routers having full topology awareness of the optical layer and could therefore control the optical layer connections.

2.2 WDM/DWDM Technology

WDM systems are divided into different wavelength patterns, conventional/coarse (CWDM) and dense (DWDM). Conventional WDM systems provide up to 8 channels in the 3rd transmission window (C-band) of silica fibers around 1550 nm.

Dense wavelength division multiplexing (DWDM) uses the same transmission window but with denser channel spacing. Channel plans vary, but a typical system would use 40 channels at 100 GHz spacing or 80 channels with 50 GHz spacing with transmission rates of up to 10 Gb/s/channel.

The channel frequencies of WDM systems have been standardized by the International Telecommunication Union (ITU) on a 100-GHz grid in the frequency range of 186 to 196 THz (covering the C and L bands in the wavelength range 1530-1612 nm).A simple WDM transmission system is shown in fig.4 which is a dispersion managed WDM link. The transmitters operating at different wavelengths are combined using a multiplexer. The multiplexed signal is launched into the fiber link for transmission to its destination, where a de-multiplexer separates individual channels and sends each channel to its own receiver [7].

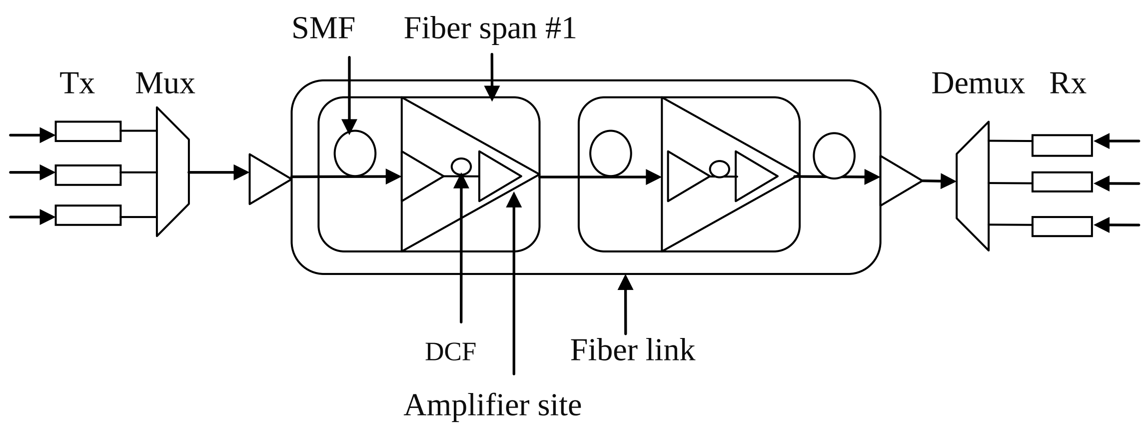


Fig.4.A simple WDM transmission system

2.3 PLI-aware Routing and Wavelength Assignment

2.3.1 Routing strategies

Routing methods are broadly classified as (i) Single-Path vs. Alternate path and (ii) Fixed vs. Adaptive.

(i) Single-Path vs. Alternate: Four standard wavelength routing algorithms that are often mentioned in the literature are;

Shortest Path (SP): For every source-destination pair, a single route that gives the shortest path distance is pre-computed and stored in the routing table. When a connection request arrives, this stored route will be selected.

Least Hop (LH): For every source-destination node pair, a single route that gives the least hop count is pre-computed and stored in the routing table. When a connection request arrives, this stored route will be selected.

Least Load Routing (LLR): For every source-destination node pair, several fixed candidate routes are pre-computed and stored in the routing table. When a connection request arrives, a search is carried out on all candidate routes. The least loaded route at the moment, defined to be one that has the most available wavelengths on its most loaded link, will be selected.

Fixed Path Least Congested (FPLC): For every source-destination node pair, several fixed candidate routes are pre-computed and stored in the routing table. When a connection request arrives, a search is carried out on all route candidates. Under the wavelength continuity constraint, the least congested route, defined to be the one that has the most available path wavelengths (available on all links of the path), will be selected.

All four algorithms can be classified as single path routing, because they only select one route upon each connection request. If this route does not work either due to wavelength unavailability or unsatisfied BER constraint, the connection request will be blocked without any further attempt.

Almost every single algorithm in the single path category can find its counterpart in the alternate category. The difference is that instead of selecting only one route, the alternate strategy prepares every node pair with a list of disjoint route candidates. If the first one does not work, the second one is examined, then the third and so on, until one route is found to be good for assignment.

Therefore we can apply the above four single path routing algorithms to the alternate domain as follows:

Alternate Shortest Path (Alt-SP): For every source-destination pair, an ordered list of routes that gives the shortest path distance, the second disjoint shortest path distance, the third disjoint, etc are pre-computed and stored in the routing table. When a connection request arrives, this stored list will be searched in order, until a route that satisfies all the requirements is found.

Alternate Least Hop (Alt-LH): For every source-destination node pair, an ordered list of routes that gives the least hop count, the second disjoint least hop count, the third disjoint, etc are pre-computed and stored in the routing table. When a connection request arrives, this stored list will be searched in order, until a route that satisfies all the requirements is found.

Alternate Least Load Routing (Alt-LLR): For every source-destination node pair, several fixed candidate routes are pre-computed and stored in the routing table. When a connection request arrives, every candidate is computed for its current load condition, and an ordered list is dynamically established with the least loaded route first and the most loaded route last. Then this list will be searched in order, until a route that satisfies all the requirements is found.

Alternate Fixed Path Least Congested (Alt-FPLC): For every source-destination node pair, several fixed candidate routes are pre-computed and stored in the routing table. When a connection request arrives, every candidate is computed for its current load conditions under the wavelength continuity constraint, and an ordered list is dynamically established with the least congested route first and the most congested route last. Then this list will be searched in order, until a route that satisfies all the requirements is found.

Clearly alternate routing increases the computation complexity for route search compared to single path routing. However, the tradeoff is usually a significantly improved blocking performance due to added redundancy.

(ii) Fixed vs. Adaptive:

Depending on how routes are found routing could be fixed or adaptive. The fixed strategy pre-defines everything in the routing tables off-line. A fixed set of routes in a fixed searching order are stored in the routing table for every source-destination node pair. Therefore, when a call arrives, the only routing action that the source node takes is to check whether the wavelength and the BER constraints are satisfied by the primary route, and if not, proceed to examine the next if there is one, and so on. Fixed routing is easy to implement with least amount of control overhead, but the blocking performance is usually degraded because of lack of traffic engineering. Typical examples of fixed routing are SP, Alt-SP, LH and Alt-LH.

The adaptive strategy, in contrast, establishes the routing table on a call-to-call basis according to the current link-state information. For algorithms like LLR, Alt-LLR, FPLC and Alt-FPLC, although their route candidates are pre-defined, the searching order is calculated adaptively based on the load condition. Hence they can be categorized under adaptive routing.

2.3.2 Wavelength Assignment Methods

The wavelength assignment subroutine operates on a set of candidate wavelengths that are given on a previously selected routing path (or paths). The set may be ordered, according to a given policy, or unordered, i.e., the wavelengths are treated in a round-robin way. Given a set of candidate paths, the wavelength selection phase can be performed either sequentially or in parallel. This is similar to the routing sub-routine. In the sequential approach, the first non-occupied wavelength that satisfies given network-layer and physical-layer constraints is selected. Such an approach is called First-Fit (FF) selection method. On the contrary, some PLI-RWA algorithms try to look through all of the candidate wavelengths so as to find the Best-Fit (BF), i.e., the most appropriate one. Finally, a random selection, which means choosing randomly amongst the available wavelengths, can be performed. It is well known that wavelength blocking probability of a random Wavelength Assignment algorithm is worse than that of the First-Fit algorithm.

2.3.3 QoS aware RWA

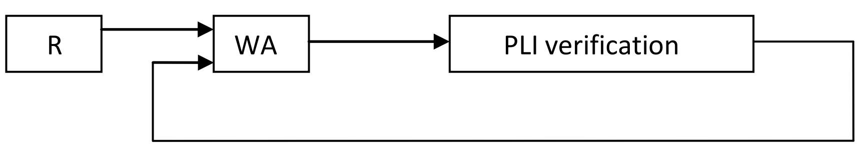
When selecting a lightpath (route and wavelength) a PLI aware RWA algorithm for a transparent network has to take into account the physical layer impairments and wavelength availability.

With static traffic, the entire set of connection requests is known in advance and the static (offline) RWA problem of setting up these connection requests is named the permanent lightpath establishment (PLD) problem.

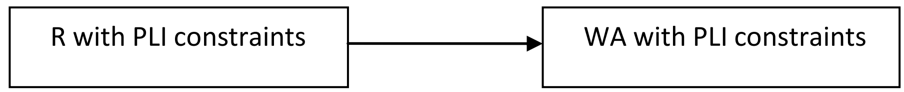
In a dynamic traffic scenario the connections are requested in some random fashion and the lightpaths have to be set up as needed. There are several heuristic algorithms proposed in the literature dealing with the wavelength assignment sub problem such as Random, First-Fit, and Least-used etc.

When the PLI's are introduced in the RWA algorithms three main approaches have been considered in the recent literature

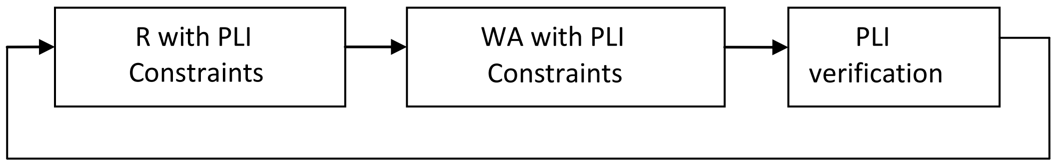
(a) Compute the route and the wavelength in the traditional way and finally verify the selected lightpath considering the physical layer impairments;
(b) Considering the PLI values in the routing and/or wavelength assignment decision and
(c) Considering the PLI values in the routing and/or wavelength assignment decision and finally also verifies the quality of the candidate lightpath. These cases are depicted in fig.5



(a)



(b)



(c)

Fig.5. Different PLI aware RWA schemes

2.3.4 Linear Impairments

The important linear impairments are: fiber attenuation, component insertion loss, amplifier spontaneous emission (ASE) noise, chromatic dispersion (CD) or group velocity dispersion (GVD), polarization mode dispersion (PMD), polarization dependent loss (PDL), crosstalk (XT) (both intra- and inter-channel), and filter concatenation (FC). Chromatic dispersion causes pulse broadening, which affects the receiver performance by reducing the pulse energy within the bit slot and spreading the pulse energy beyond the allocated bit slot leading to inter-symbol interference (ISI).

PMD is not an issue at 10Gbps but as the bit rate increases to 40Gbps or higher it does become an issue. In general, in combination with PMD there is also PDL which can cause optical power variation, waveform distortion and signal-to-noise ratio fading.

Imperfect optical components i.e., filters, de-multiplexers and switches inevitably introduce some signal leakage either as inter-channel or intra-channel crosstalk in WDM transmission systems.

Filter concatenation is concatenation of filters along the lightpath which tends to reduce the overall passband of the filters. This also makes the transmission system susceptible to filter passband misalignment due to device imperfections, temperature variations and aging.

2.3.5 Non-Linear Impairments

The most important non-linear impairments are self phase modulation (SPM), cross phase modulation (XPM), four wave mixing (FWM), stimulated brillouin scattering (SBS) and stimulated Raman scattering (SRS).

The nonlinear phase shift manifests as phase modulation. In SPM the phase of the signal is modulated by its own intensity; while in XPM the signal phase is modulated by the intensity of other signals. The primary effect of these impairments is pulse broadening in frequency domain without changing the shape of the signal.SBS and SRS involve non elastic scattering mechanism. These impairments set an upper limit on the amount of optical power that can be launched into an optical link.

2.4 Crosstalk and ASE noise in all-optical networks

2.4.1 Amplifier Spontaneous Emission (ASE) noise

In optically amplified systems, erbium doped fiber amplifiers (EDFA) are used to provide sufficient gain to compensate for the power loss and extend the range of signal transmission. This amplifier acts as a source of additive ASE noise which affects the signal quality**.** This noise is often quantified with noise figure (NF).The NF is a factor which says how much higher the noise power spectral density of the amplified output is compared with the input noise power spectral density times the amplification factor and is often specified in decibels (dB) [9]. ASE noise is emitted by the amplifier in both directions, but only the forward ASE is a direct concern to system performance since that noise will co-propagate with the signal to the receiver where it degrades system performance. Counter-propagating ASE can, however, lead to degradation of the amplifier's performance since the ASE can deplete the inversion level and thereby reduce the gain of the amplifier. Excess ASE is an unwanted effect in lasers, since it dissipates some of the laser's power. In optical amplifiers, ASE limits the achievable gain of the amplifier and increases its noise level. The ASE noise mixes with the optical signal and produces beat noise components at the square-law receiver. The ASE noise is very broadband (~40 *nm*) and needs to be carefully analyzed to evaluate its degrading effect on system performance.

2.4.2 Crosstalk in multi-wavelength switched networks

There are two potential sources for generating optical crosstalk in an OXC. One is the crosstalk from the optical space switches and the other is due to non-ideal wavelength filtering [8]. Filter associated crosstalk from the two immediately adjacent wavelength channels considering four signal wavelengths (λ_1,λ_2, λ_3, λ_4) with λ_2 as the desired signal.After the non-ideal filtering,λ_2 carrier suffers crosstalk from λ_1 *and* λ_3 which enter the multiwavelength transport network node on the same input fiber.In a similar manner crosstalk coupling occurs in other channels. Fig 6 shows the effect of crosstalk.

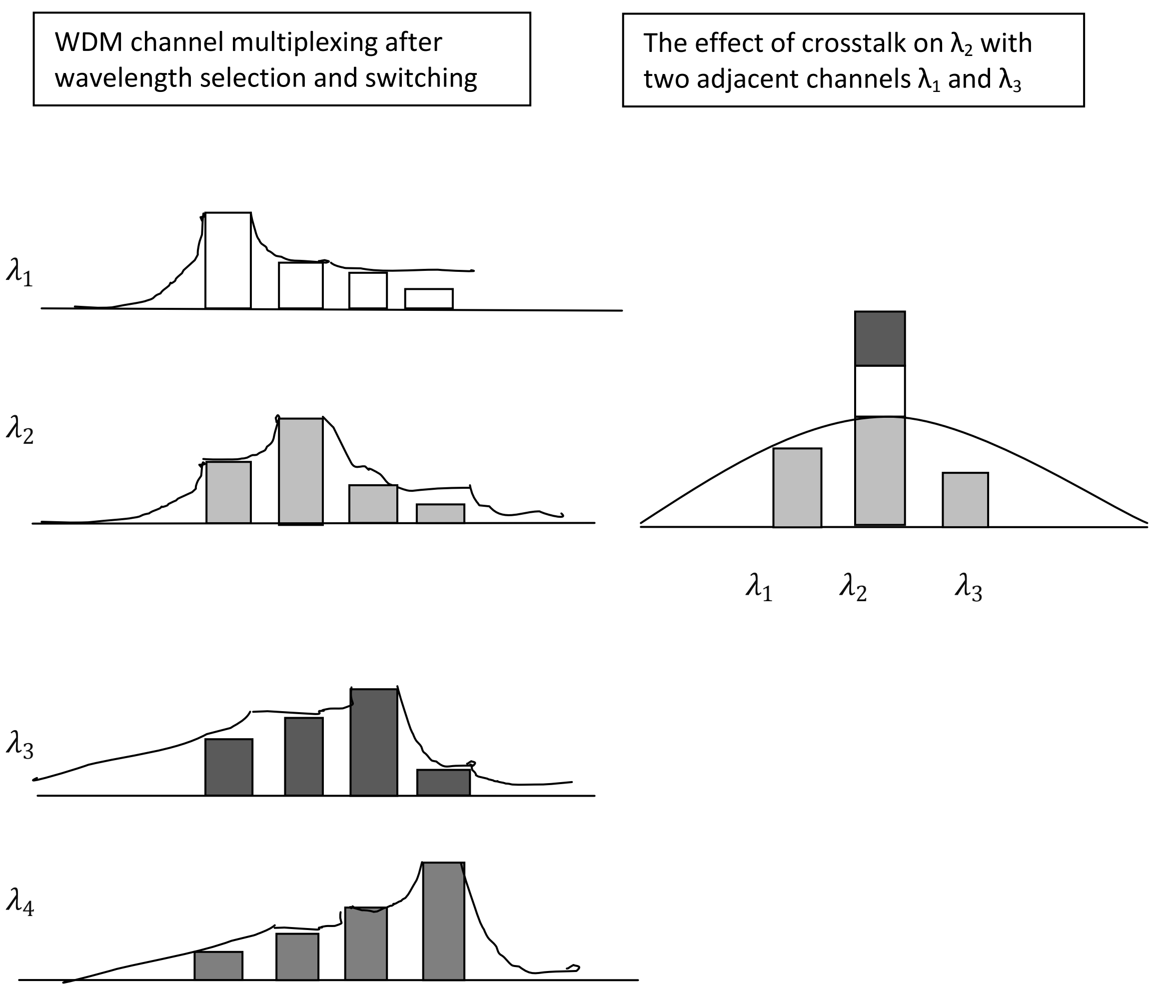


Fig.6 Crosstalk due to the non-ideal filtering

The two types of component crosstalk are (i) HEC or hetero-wavelength and (ii) HOC or homowavelength.HEC arises from the channels on same i/p route but operating at different wavelengths.HOC arises from the optical cross connect nature of the node involving different i/p fibers and the crosstalk signals occupy the same nominal wavelength as the desired signal.

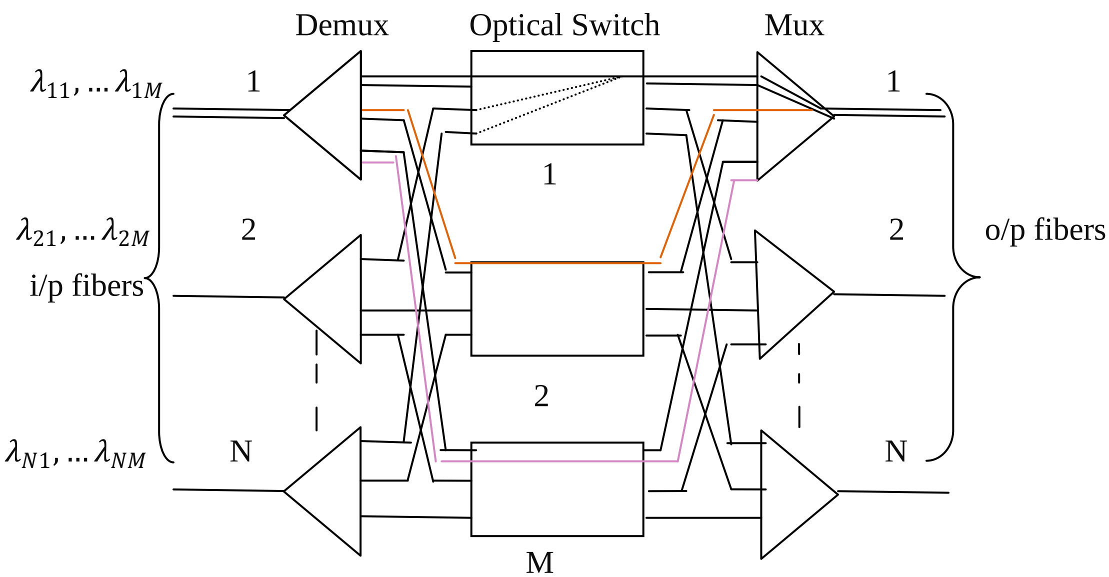


Fig 7.Crosstalk generation in OXC

Linear crosstalk arises due to incomplete isolation of WDM channels by optical components such as OADMs, OXCs, multiplexers/demultiplexers, and optical switches, i.e., the effect of signal power leakage from other WDM channels on the desired channel [9]. It is different from non-linear crosstalk involving non-linear fiber interaction (such as cross-phase modulation, stimulated Raman scattering, etc.). Linear crosstalk depends on the ratio of the optical powers of two channels, whereas non-linear crosstalk depends on absolute powers. Linear crosstalk can be either incoherent (i.e., hetero-wavelength or out-of-band) or coherent (i.e., homo-wavelength or in-band). Consider a case in which a tunable optical filter is used to select a single channel among the W channels incident on it. If the optical filter is set to pass the k^{th} channel, optical power reaching the output of the filter can be written as $P = P_k + \sum_{w \neq k}^{W} T_{kj} P_j$ where P_k is the power in the k^{th} channel and T_{kj} is the filter transmittivity for channel j when the channel k is selected. For an ideal filter T_{kj} should be zero. Crosstalk occurs if $T_{kj} \neq 0$ for j $\neq k$. This is out-of-band crosstalk because it belongs to the channels lying outside the spectral band occupied by the channel selected. It is incoherent because it depends only on the power of the neighboring channels. The in-band crosstalk can be easily understood by considering a typical structure of an OXC without in-built amplifiers as shown in Fig 7. The OXC consists of N fiber ports and M optical switches. Wavelength 1 in input fiber 1, denoted by λ_{11}, is affected by the $N-1$ crosstalk components due to the leakage from the $N-1$ signals with wavelength 1 on the other $N-1$ input fibers, $\lambda_{21}, \lambda_{31}...,\lambda_{N1}$, when passing through the optical switch 1 (shown in dotted lines). Similarly, when wavelength 1 is demultiplexed to one path, there will be a fraction of it in each of the other $M-1$ outputs of the corresponding demultiplexers. Passed through the optical switches, the main signal is multiplexed with $M-1$ signals with different wavelengths. At the same time, the $M-1$ crosstalk contributions of wavelength 1in these $M-1$ paths are combined with the main signal (shown in orange and blue lines). Assume ε is the isolation of multiplexers/demultiplexers, P is power of the input signal, and then the crosstalk contributions are $\varepsilon^2(M-1)\,P$. The computation of crosstalk becomes quite complicated as the number of crosstalk elements which the signal passes through increases, and should be considered in the design of WDM networks. Crosstalk effects can be mitigated by the use of intelligent wavelength assignment techniques.

CHAPTER 3

ADAPTIVE ROUTING AND WAVELENGTH ASSIGNMENT

Network Model

Q-Factor

Proposed Mechanism

Algorithm

ADAPTIVE ROUTING AND WAVELENGTH ASSIGNMENT

3.1. Network Model

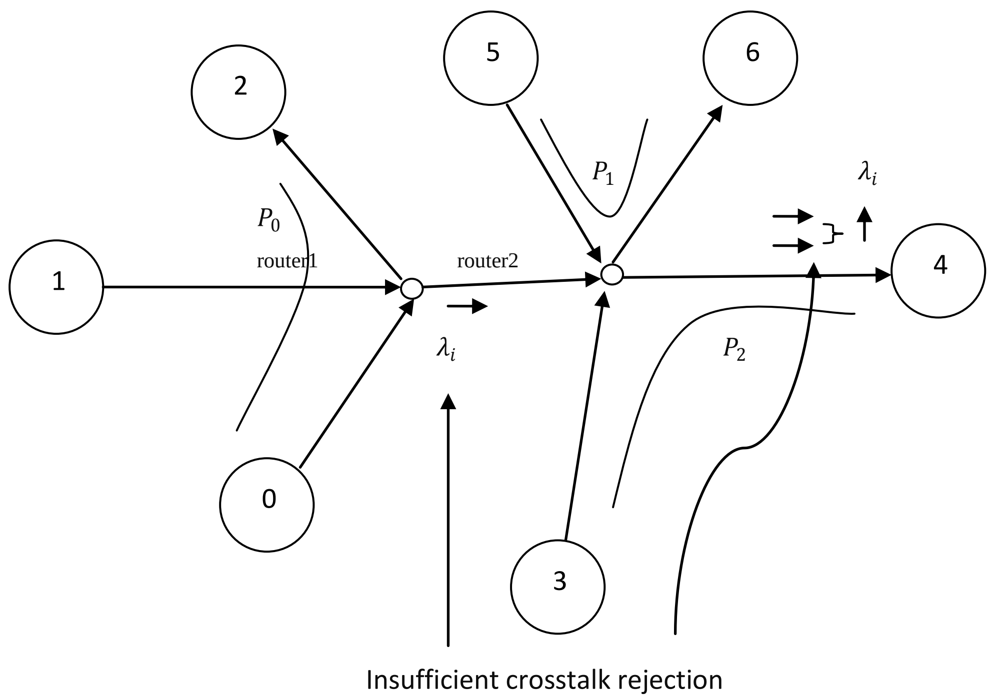


Fig.8.example of an optical network that may induce component crosstalk

Crosstalk signals generated at the routers propagate through the links; it is assumed that all the routers inject crosstalk signals with equal power level. The performance analysis of unequally powered interfering crosstalk signals has been considered in the literature. Even though crosstalk signal suffers power loss the inline optical amplifiers provide sufficient gain along the transmission path which causes it to accumulate along the lightpath. Optical amplifiers in the path inject ASE noise and a link may have one or more fiber spans separated by the amplifiers.

Fig.8 shows a schematic configuration of an optical network that may induce component crosstalk [10]. Three lightpaths are shown having the same wavelength λ_i with

$P_0, P_1\ and\ P_2$ established between the nodes (0, 2), (5, 6) and (3, 4) respectively. Due to non-ideal characteristics the crosstalk signal generated at the router1 appears as a component crosstalk at the wavelength router2.

3.2 Q-Factor

Let μ_0,μ_1,σ_0 and σ_1 be the means and standard deviations of the "0" and "1" samples after reception. Then the Q-Factor is given by [11]

$$Q - Factor = \frac{\mu_1 - \mu_0}{\sigma_0 + \sigma_1} \tag{1}$$

Where, the variance ${\sigma_0}^2 = {\sigma_1}^2 = {\sigma_{s-sp}}^2 + {\sigma_{s-xt}}^2 + {\sigma_{xt-xt}}^2 + {\sigma_{sp-xt}}^2 + {\sigma_{sp-sp}}^2$ for samples "0" and "1" respectively. Usually ${\sigma_{xt-xt}}^2$, ${\sigma_{sp-xt}}^2$ and ${\sigma_{sp-sp}}^2$ have negligible effect and hence ignored. For an infinite extinction ratio (P_1/P_0),${\sigma_{s-sp}}^2$ and ${\sigma_{s-xt}}^2$ vanish for the contribution of ${\sigma_0}^2$. ${\sigma_{s-sp}}^2$,${\sigma_{s-xt}}^2$, ${\sigma_{xt-xt}}^2$, ${\sigma_{sp-xt}}^2$,${\sigma_{sp-sp}}^2$ are the variances of the beating noise at the receiver between the main signal and ASE noise, signal and crosstalk, crosstalk and crosstalk, ASE noise and crosstalk, ASE noise and ASE noise respectively.

3.3 Proposed Mechanism

In QoS constrained all-optical paths, calls can be blocked either because there is no wavelength available or the BER of the lightpath is very high to establish the call between the source-destination pair. Because both crosstalk and wavelength availability depend on the network state, it is important that such RWA algorithms consider only those routes that can meet the wavelength continuity constraint and that dynamically accounts for QoS at route establishment time. Such RWA algorithms are said to be adaptive, as opposed to the classical RWA algorithms where routing is fixed during the network operation and a wavelength is then chosen to try to accommodate arriving calls.

In our approach the Q-Factor of a candidate lightpath is computed during the admission phase of a call. Once a call has been setup in the network, its Q-Factor could vary slightly depending on the instantaneous traffic in the network, typically the Q-Factor of the existing call in the network may decrease slightly when a new call is established and it may increase slightly when another ongoing call leaves the network. The adaptive RWA algorithm employed in this work ensures that a call is set-up on a good route and wavelength when it is admitted into the network.

Adaptive routing and wavelength assignment is a technique where the choice of a route depends on the network state [11]. This means that a wavelength is chosen according to a policy (in this case First-Fit selection method, where the wavelength is pre-ordered) and a shortest route is computed in an altered topology which contains only the links from the original topology where the considered wavelength can be used. Q-Factor of an existing call gets affected when a new call arrives with the same wavelength; hence the Q-Factor is estimated to ensure that it is above a threshold (usually 6 which gives a min BER of10^{-9}) for all calls including the current call.

3.4 Algorithm

Using a standard graph theory to describe the algorithm we refer to a network as a directed graph$G = (V, E)$, where V is a set of vertexes (nodes) and E is a set of edges (links).

A path $\pi(s,d)$ of length $l\big(\pi(s,d)\big) = \|\pi(s,d)\|$ is defined as a sequence of n distinct edges e_i joining s and d, where $s, d \in V$,$e_i \in E$ and $\pi(s,d) = \{e_1, e_2, e_3, \dots e_n\}$.

Let $\Pi(s,d) = \{\pi_i(s,d)\}$ be a set of paths from node s and d.

We begin with a topology matrix whose elements represent the physical distance between a source-destination pair.

$$T = \{l(i,k)\} \tag{2}$$

where $l(i,k)$ is the physical distance of link k of node i.

Let $\Lambda = \left\{\lambda_j, j = 1, \dots L\right\}$ be the ordered set of wavelengths where we make use of First-Fit Algorithm.

for $\lambda_j \in \Lambda$ **do**

$$\text{Altered\_T}\ (i,k) = \begin{cases} T(i,k), & \lambda_j\,(i,k) = 0 \quad \text{(wavelength unused)} \\ \\ 0, & \lambda_j\,(i,k) = 1 \quad \text{(wavelength used)} \end{cases} \tag{3}$$

Find $\Pi^{\lambda_j}(s,d) \quad = \{\pi_i(s,d)\}$ (4)

for SP, alternate route (i=2), k-SP (i=k =7), and all possible paths.

Check if Q-Factor $(\pi(s_i,d_i),\lambda_j)$> 6 where $\pi(s_i,d_i)$ represents all the affected lightpaths including the tentative lightpath.

Mark $(\pi_i(s,d),\lambda_j)$ as usable

endfor

$$(\Pi(s,d),\lambda) = \{(\pi_j(s,d),\lambda_j\} \tag{5}$$

Among the usable lightpaths, a lightpath is chosen according to the following policies.

Shortest-Path (SP) policy:-$(\pi(s,d),\lambda)$= $\min_{\substack{\pi\in\Pi(s,d) \\ \lambda\in\Lambda}}(l(\pi,\lambda))$ (6)

Optimum Q-factor policy:-$(\pi(s,d),\lambda)$= $\max_{\substack{\pi\in\Pi(s,d) \\ \lambda\in\Lambda}}(Q-Factor(\pi,\lambda))$ (7)

Least Q-factor policy:-$(\pi(s,d),\lambda)$= $\min_{\substack{\pi\in\Pi(s,d) \\ \lambda\in\Lambda}}(Q-Factor(\pi,\lambda))$ (8)

CHAPTER 4

SIMULATION AND RESULTS

Simulated Topology

Simulation Result for Shortest Path method

Simulation Result for Alternate Route method

Simulation Result for k-SP method

Simulation Result for disjoint route method

SIMULATION AND RESULTS

4.1 Simulated Topology

We consider a 9-node network topology for simulation with the numbers on the links specifying the number of spans between two nodes. Here the span length is taken as 70km. Table.1 shows the physical parameters used for simulation purpose [11].

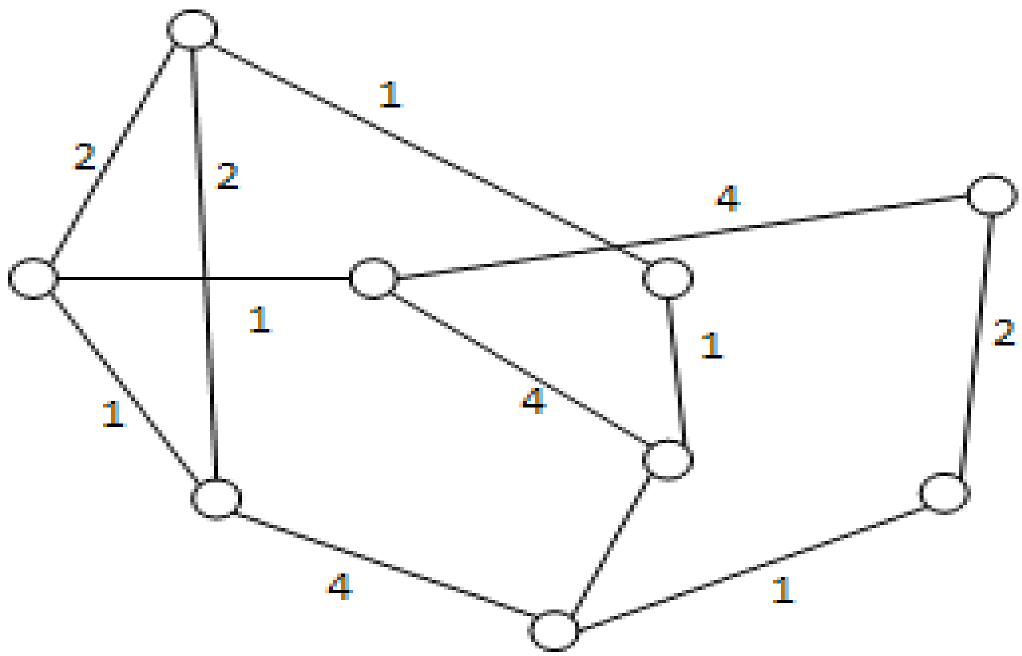


Fig.9.Topology considered for simulation with the number specifying the number of spans with a span length of 70km.

TABLE1

Physical parameters for the simulated network

Description	Value
Crosstalk level	-25dB
Number of wavelengths	10,12
Minimum Q-factor	6
Extinction ratio	∞
Receiver’s responsivity	1
Signal peak power	1mW
Decision threshold	0.5mA

4.2 Simulation Result for Shortest Path method

Fig.10, 11 shows the blocking probability for different policies. It is very clear from both the figures that for all the policies as the number of call requests increase so does the blocking probability. This is due to wavelength insufficiency. Fig.11 shows that increase in number of wavelengths used lowers the blocking probability.

In Fig.10 Optimum Q-Factor has a lower blocking probability compared to the other two policies. Optimum Q-Factor performs better because a path with highest Q-Factor is chosen among a set of usable lightpaths and hence when another call is established in the network on the same wavelength the possibility of the Q-Factor of the already existing call reducing below the threshold is lower compared to the other two policies, where in case of LQ policy the path and the wavelength are chosen such that its Q-Factor is lowest among the set of lightpaths. Hence very few crosstalk components are required to bring the Q-Factor of the existing call below the threshold which tends to increase the blocking probability due to high BER. As far as resource utilization is concerned LQ allows for all the future calls to have a better quality transmission path. Overall, due to the tradeoff Least Q-Factor policy is slightly inferior compared to the Optimum-Q and the SP policy.

4.2 Simulation result for shortest path method

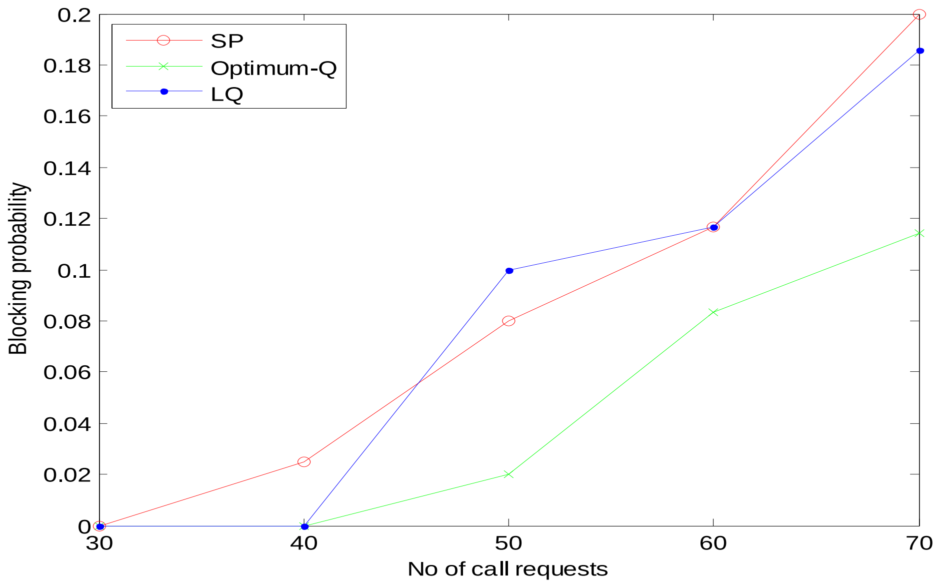


Fig.10 Blocking probability for SP method when the number of wavelengths = 10

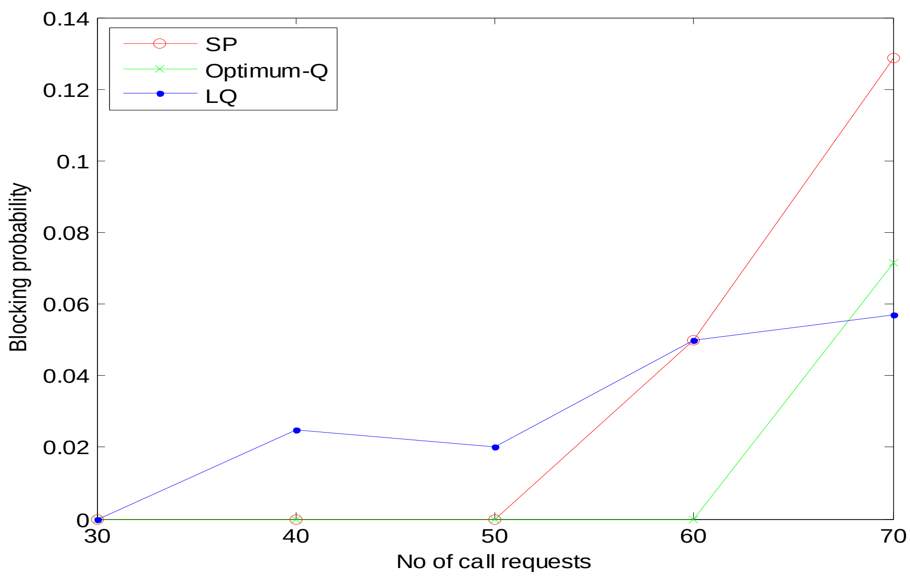


Fig.11 Blocking probability for SP method when the number of wavelengths = 12

Table 2, 3 gives the Q-Factor values for Optimum-Q policy and LQ policy show for certain paths. Comparison shows a relatively higher value for Optimum-Q policy compared to the LQ policy.

TABLE.2

Routing strategy: Shortest Path

Policy: Optimum Q-Factor policy

S D	Path Reference Number	Path	Physical distance(no. of spans)	Q-Factor
1 5	1 2	1-3-6-5 1-7-5	3 6	11.83 14.64
7 6	1 2	7-5-6 7-8-9-6	3 5	8.65 25.47
5 2	1 2	5-4-2 5-6-3-2	3 6	9.91 12.05

TABLE.3

Routing strategy: Shortest Path

Policy: Least Q-Factor policy

S D	Path Reference Number	Path	Physical distance(no. of spans)	Q-Factor
6 8	1 2	6-9-8 6-5-4-8	4 6	8.71 9.20
9 7	1 2	9-8-7 9-6-3-1-7	3 8	14.13 6.63
5 1	1 2	5-6-3-1 5-7-1	3 6	9.31 6.84

4.3 Simulation Result for Alternate Route method

Fig 12, 13 shows the results for the case of alternate route strategy i.e., during route computation a single redundant path is pre-computed and stored in the routing table. When the shortest path does not satisfy the QoS criteria, the second path is used to check if a lightpath is feasible. As the number of call requests increase so does the blocking probability. Fig.13 shows that increasing the number of wavelengths shows reduced blocking probability for a certain number of call requests. Even in this case Optimum-Q and SP show a better performance compared to the LQ policy. Compared to the SP routing strategy this method does not provide any improvement in the blocking performance. By selecting a longer path the increase in the number of crosstalk components that are injected into the network when a connection request arrives tends to lower the Q-Factor for all the affected lightpaths hence increasing the blocking probability.

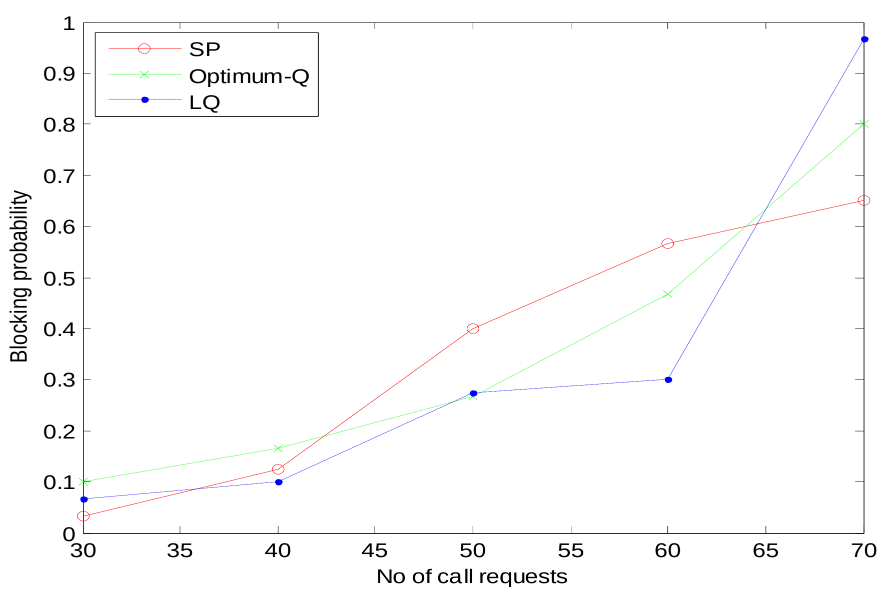


Fig.12 Blocking probability for alternate route method when the number of Wavelengths = 10

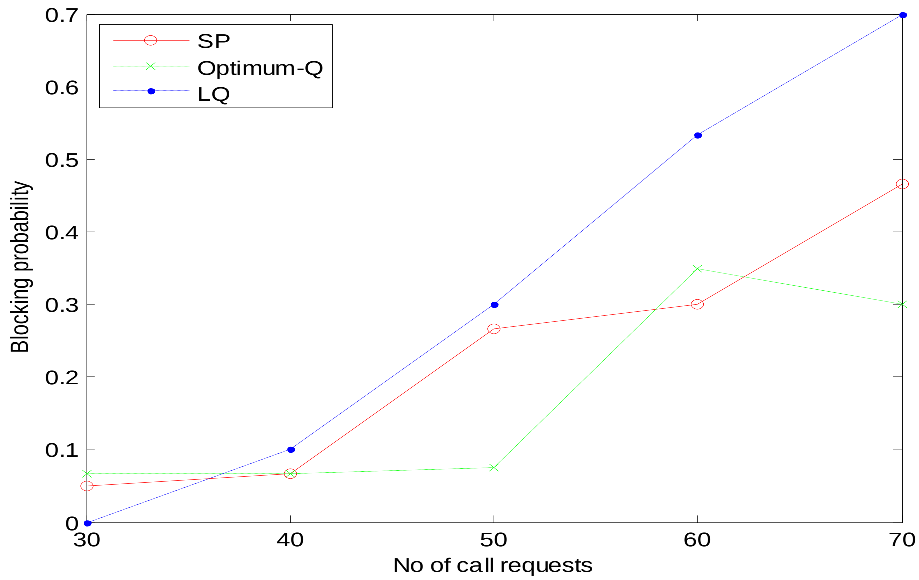


Fig.13 Blocking probability for alternate route method when the number of Wavelengths = 12

4.4 Simulation Result for k-SP method

Fig 14, 15 shows the blocking probability for k-SP where we have chosen arbitrarily k = 7. Increase in number of call requests shows that the blocking probability increases. When the number of wavelengths is increased the blocking probability reduces since more lightpaths are available to establish a call. The blocking probability of Optimum-Q and SP policy are better compared to the LQ policy .With increased route computation complexity the performance is similar to alternate route with further increase in the overall blocking probability. Increasing the number of routes available for a particular wavelength does not provide any advantage compared to the SP routing strategy.

4.4 Simulation Result for k-SP route method

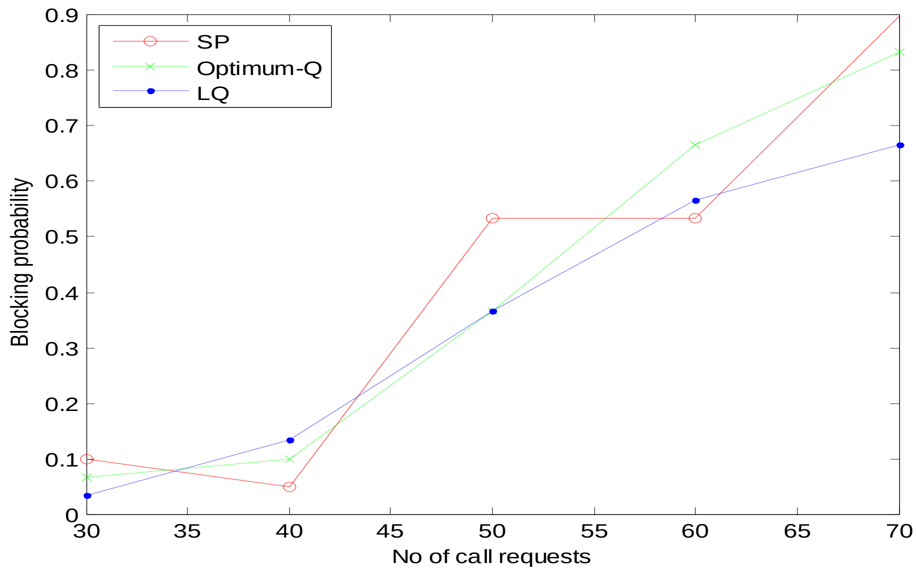


Fig.14 Blocking probability for k-SP (k=7) method when the number of wavelengths =10

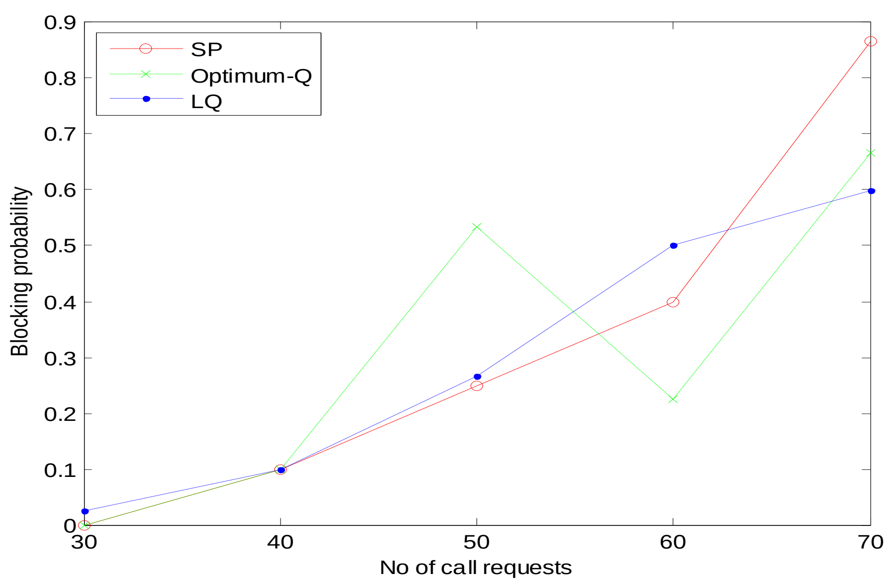


Fig.15 Blocking probability for k-SP (k=7) method when the number of wavelengths=12

4.5 Simulation Result for disjoint route method

Fig 16, 17 shows the blocking probability for disjoint (all possible path) route where all the routes between an s-d pair are pre-computed and stored in a routing table. The blocking probability of Optimum-Q and SP are better compared to the LQ policy. This is due to the fact that Optimum-Q chooses a path with highest Q-Factor from a set of lightpaths. With increased route computation complexity the performance is similar to alternate route and k-SP with further increase in the overall blocking probability. This is due to that fact that selection of a longer path injects more crosstalk components into the system which tend to lower the Q-Factor value of the already established call.

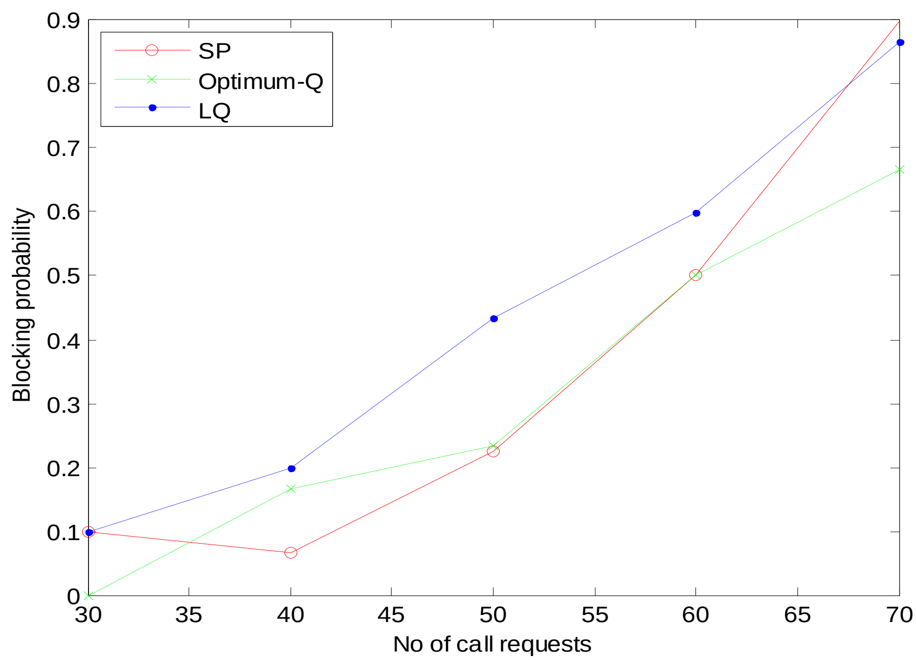


Fig.16 Blocking probability for disjoint route method when the number of Wavelengths = 10

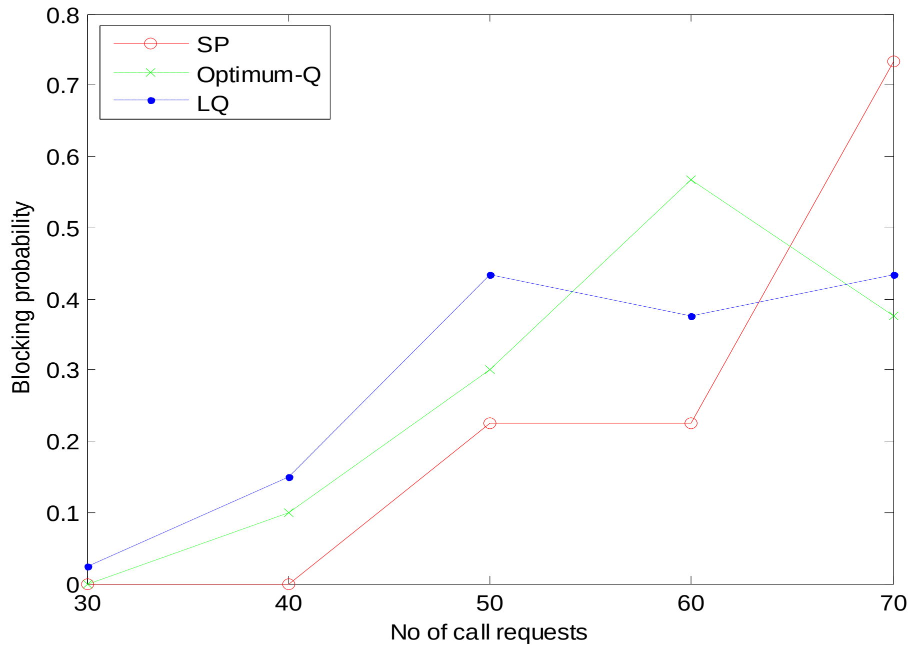


Fig.17 Blocking probability for disjoint route method when the number of Wavelengths = 12

Table 4, 5 gives the Q-Factor values for Optimum-Q policy and LQ policy. Q-Factor values for paths selected using Optimum-Q policy are higher compared to LQ policy.

TABLE.4

Routing strategy: All possible paths

Policy: Optimum Q-Factor policy

S D	Path Reference Number	Path	Physical distance(no. of spans)	Q-Factor
7 8	1	7-8	1	19.88
	2	7-1-2-3-6-9-8	11	27.32
4 5	1	4-5	1	33.50
	2	4-8-7-1-3-6-5	12	25.83
1 7	1	1-7	4	28.57
	2	1-2-4-5-7	6	22.55
	3	1-2-3-6-5-7	9	36.33

4.5 Simulation Result for disjoint route method

TABLE.5

Routing strategy: All possible paths

Policy: Least Q-Factor policy

S D	Path Reference Number	Path	Physical distance(no. of spans)	Q-Factor
5 1	1	5-4-2-1	4	23.08
	2	5-6-3-2-1	7	18.02
4 5	1	4-5	1	25.42
	2	4-2-1-7-5	9	25.37
3 9	1	3-6-9	3	18.02
	2	3-1-7-8-9	8	24.87

CHAPTER 5

CONCLUSION AND FUTURE WORK

Conclusion

Future Work

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The performance of different adaptive RWA algorithms has been evaluated in terms of blocking probabilities in the presence of in-band crosstalk and ASE noise. Optimum-Q policy shows better QoS performance compared to LQ and SP policies. With different methods of route computation shortest path seems to provide reduced blocking probability and reduced computational complexity compared to the other methods. Although adaptive RWA algorithms are computationally intensive they are better suited for the automatically switched optical networks.

5.2 Future Work

This work could be extended to include other linear and non-linear impairments to further evaluate the blocking performance .We propose to improve upon the Q-Factor model when non-linearity is included in the evaluation of the network performance.

BIBLIOGRAPHY

Bibliography

[1] S. Azodolmolky, M. Klinkowski, Eva Martin, Davide Careglio, Josep Pareta and Ionnis Tomkos, ”A survey on physical layer impairments aware routing and wavelength assignment algorithms in optical networks” , *Computer Networks*, 2009.

[2] J.C.Attard, J.E.Mitchell and C.J.Rasmussen, ”Performance analysis of interferometric noise due to unequally powered interferers in optical networks”, *Journal of Lightwave Technology*, vol.23, no.4, 2005.

[3] I. Tomkos, ”Performance Engineering of Metropolitan Area Optical networks through Impairment Constraint Routing”, IEEE *Communication, Mag. (Optical Supplement)*, Aug 2004.

[4] Marcelo R.Jimenez, Rogerio Passy, Marco A. Grivet, J.P.Weid, ”Computation of power penalties due to intra-band crosstalk in optical systems”, *IEEE photonics technology letters*,vol.15,no.1,2003.

[5] Tao Deng and Suresh Subramaniam, ”Adaptive QoS routing in dynamic wavelength routed optical networks”, *Proceedings Broadnets*, 2005.

[6] Rajiv Ramaswami, ”Optical fiber communication: From Transmission to Networking”, IEEE Communications Magazine, 2002.

[7] G.P.Agarwal, ”Lightwave Technology Telecommunication Systems”, Wiley Inter-Science, 2005.

[9] Saradhi and Subramaniam, ”Physical Layer Impairment Aware Routing (PLIAR) in WDM optical networks: Issues and Challenges”, IEEE communications surveys and tutorials, vol .11, no.4, 2009

[10] Santu Sarkar and Nikhil R Das, ”Study of component crosstalk and obtaining detection threshold for minimum BER in a WDM receiver”, *Journal of Lightwave Technology*, vol.27, no.19, 2009.

[11] Yvan Pointurier, Brandt-Pearce, Tao Deng and Suresh Subramaniam, ”Fair QoS-aware adaptive routing and wavelength assignment in all optical networks”, *Proc.ICC*, 2006.

[12] Y.Huang, ”Connection Provisioning with Transmission Impairment Consideration in Optical WDM networks with High-Speed Channels”, *IEEE/OSA Journal of Lightwave Technol.*, vol.23, no.3, pp.982-993, Mar 2005.

[13] Dietrich Marcuse, ”Derivation of analytical expressions for the bit error probability in lightwave systems with optical amplifiers”, *Journal of Lightwave Technology*, vol.8, no.12, 1990.

[14] Yvan Pointurier and Brandt Pearce, ”Analytical study of crosstalk propagation in all-optical networks using perturbation theory”, Journal *of Lightwave Technology*, vol.23, no.12, 2005.

[15] P. Kulkarni, A. Tzanakaki, C. MasMachuka and I. Tomkos,”Benefits of Q-Factor based routing in WDM metro networks”, ECOC *2005 Proc*, vol.4.

[16] Yun feng Shen, K Lu and Wanyi Gu, ”Coherent and Incoherent crosstalk in WDM optical networks”, Journal *of Lightwave Technology*, vol.17, no.5, 1999.

[17] Byrav Ramamurthy, Debasish Datta, Helena Feng, Jonathan P.Heritage, Biswanath Mukerjee, ”Impact of Transmission impairments on the Tele-Traffic performance on wavelength-routed optical networks”, *Journal of Lightwave Technology*, vol.17, no.19, 1999.